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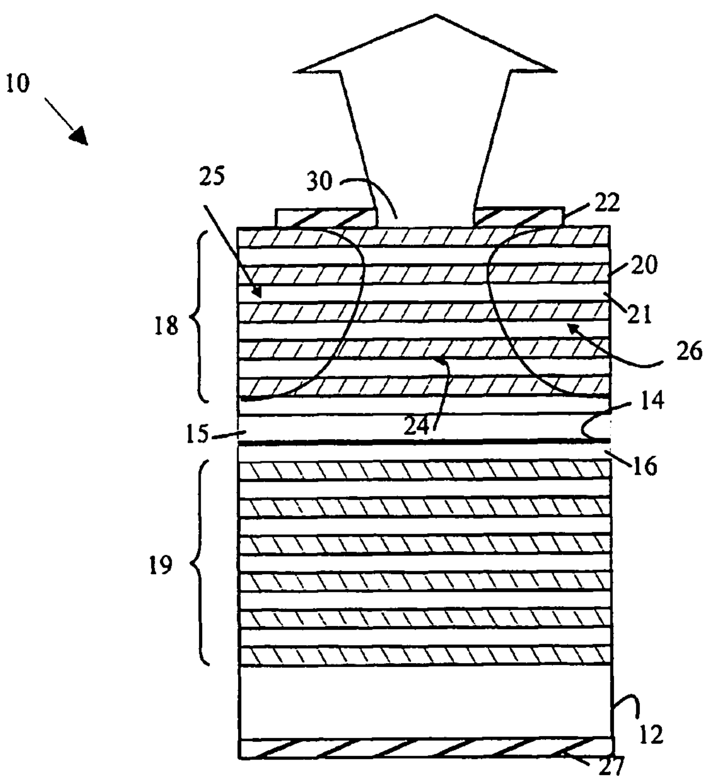
(54) Title: VERTICAL-CAVITY SURFACE EMITTING LASER HAVING IMPROVED LIGHT OUTPUT FUNCTION



(57) Abstract: A laser diode (300) that includes a light guiding structure that improves the light-output-versus-current curve by altering the multiple spatial modes of the laser diode (300). A laser diode according to the present invention includes a bottom mirror (19) constructed on an electrically conducting material, an active region constructed from a first conductive spacer (16) situated above the bottom mirror (19), a light emitting layer (14), and a second conductive spacer (15) situated above the light emitting layer. The laser diode also includes a top mirror (18) constructed from a plurality of mirror layers of a semiconducting material of a first conductivity type that are located above the second conductive spacer. The adjacent mirror layers have different indexes of refraction. One or more of the top mirror layers is altered to provide an aperture defining layer (301) that includes an aperture region that alters the spatial modes of the device.

WO 03/010864 A1

VERTICAL CAVITY SURFACE EMITTING LASER HAVING IMPROVED LIGHT OUTPUT FUNCTION

FIELD OF THE INVENTION

This invention relates generally to vertical cavity surface-emitting lasers (VCSELs) and, more particularly, to an improved VCSEL in which the current channeling function utilizes an ion-implanted or diffused aperture region.

BACKGROUND OF THE INVENTION

Semiconductor laser diodes were originally fabricated in a manner that led to a diode structure in which light is emitted parallel to the surface of the semiconductor wafer with a cavity constructed from mirrors that are perpendicular to the surface of the substrate. Unfortunately, this structure does not lend itself to low cost "mass" manufacturing or to the cost-effective fabrication of two-dimensional arrays of laser diodes.

These problems are overcome by a class of laser diodes that is fabricated such that the laser structure is perpendicular to the surface of the semiconductor wafer and the light is emitted perpendicular to the surface. These laser diodes are commonly known as Vertical Cavity Surface-Emitting Lasers (VCSELs). A VCSEL may be viewed as a laser having mirrors constructed from alternating layers of material having different indices of refraction. These lasers are better suited for the fabrication of arrays of lasers for displays, light sources, optical scanners, and optical fiber data links. Such lasers are useful in optical communication systems for generating the light signals carried by optical fibers and the like.

Compared to conventional edge-emitting semiconductor lasers, VCSELs have a number of desirable characteristics. The use of multi-layered DBR mirrors to form a cavity resonator perpendicular to the layers eliminates the need for the cleaving operation commonly used to create the cavity mirrors used in edge emitting lasers. The orientation of the resonator also facilitates the wafer-level testing of individual lasers and the fabrication of laser arrays.

To achieve high-speed operation and high fiber-coupling efficiency, it is necessary to confine the current flowing vertically in the VCSEL, and thus the light emission, to a small area. There are two basic prior art current confinement schemes for VCSELs. In the first scheme, a conductive aperture is defined by means of an ion-implanted, high-resistivity region in the semiconductor Distributed-Bragg-Reflector (DBR) mirror. Such a scheme is taught in Y. H. Lee, *et al.*, **Electr. Lett. Vol. 26**, No. 11, pp. 710-711 (1990), which is hereby incorporated herein by reference. In this design small ions (e.g. protons) are deeply implanted (e.g. 2.5 to 3 μm) in the DBR mirror. The implantation damage converts the semiconductor material through which the ions traveled to highly resistive material. Current is provided to the light generation region via an electrode that is deposited on the top surface of the VCSEL.

Unfortunately, ion-implanted VCSELs exhibit multiple spatial modes, which lead to a light-output-versus-current curve that often displays kinks due to the random and varying nature of the multiple spatial modes. This kinky light-output-versus-current behavior can produce a "noisy" waveform, and can degrade the performance of optical communication systems based on such designs. Prior art devices have been proposed to reduce the kinks in the light-output-versus-current characteristics by introducing additional structure in the light-emitting area; however, such solutions increase the cost and complexity of the devices.

In the second design, the current confinement aperture is achieved by generating a high-resistivity oxide layer embedded in the semiconductor DBR mirror. Such a scheme is taught in D. L. Huffaker, *et al.*, **Appl. Phys. Lett.**, vol. 65, No. 1, pp. 97-99 (1994) and in K. D. Choquette, *et al.*, **Electr. Lett., Vol. 30**, No. 24, pp.2043-2044 (1994), both of which are incorporated herein by reference. In this design, an annular insulating ring having a conducting center is generated by oxidizing one or more layers of Al-containing material in the DBR mirror in a high-temperature wet Nitrogen atmosphere. The size of the oxide aperture is determined by the Al concentration of the Al-containing layers, the temperature, the moisture concentration of the oxidizing ambient, and the length of the oxidation time. The oxidation rate is very sensitive to all of these parameters, and hence, the oxidation process is not very reproducible. As a result, device yields are less than ideal. In addition, the oxidization process leads to stress within the device, which can further reduce yields.

Broadly, it is the object of the present invention to provide an improved VCSEL and method for making the same.

The manner in which the present invention achieves its advantages can be more easily understood with reference to the following detailed description of the preferred embodiments of the invention and the accompanying drawings.

SUMMARY OF THE INVENTION

The present invention is a laser diode that includes a light guiding structure that improves the light-output-versus-current curve by altering the multiple spatial modes of the laser diode. A laser diode according to the present invention includes a bottom mirror constructed on an electrically conducting material, an active region constructed from a first conductive spacer situated above the bottom mirror, a light emitting layer, and a second conductive spacer situated above the light emitting layer. The laser diode also includes a top mirror constructed from a plurality of mirror layers of a semiconducting material of a first conductivity type that are located above the second conductive spacer. The adjacent mirror layers have different indexes of refraction. One or more of the top mirror layers is altered to provide an aperture defining layer that includes an aperture region and an implant region, the aperture region includes an aperture semiconducting material of the first conductivity type, the implant region surrounds the aperture region and includes an implant material that alters the reflectivity of the mirror layers in the implant region, the implant region having a resistivity of less than 5×10^6. The aperture defining layer is preferably located within a distance equal to 20 mirror layers of the light emitting layer. The implant material is preferably an element chosen from the group consisting of Cr, Ti, and Fe.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross-sectional view of a conventional ion-implanted VCSEL 10.

Figure 2 is a cross-sectional view of an ion-implanted VCSEL 300 that utilizes a mode smoothing layer 301 according to the present invention.

Figures 3(A)-3(E) are cross-sectional views of a VCSEL according to the present invention at various stages in the fabrication process.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention may be more easily understood with reference to Figure 1, which is a cross-sectional view of a conventional VCSEL 10. Since construction of VCSELs is well known to those skilled in the laser arts, it will not be described in detail here. For the purposes of this discussion, it is sufficient to note that VCSEL 10 may be viewed as a p-i-n diode having a top mirror region 18, a light generation region 14, and bottom mirror region 19. These regions are constructed on a substrate 12. Electrical power is applied between electrodes 22 and 27. The various layers are constructed by epitaxial growth. Substrate 12 is an n-type semiconductor in the example shown in Figure 1.

The active region is typically constructed from a layer having one or more quantum wells of InGaAs, GaAs, AlGaAs, InGaAsN, or InAlGaAs that is separated from mirror regions 18 and 19 by spacers 15 and 16, respectively. The choice of material depends on the desired wavelength of the light emitted by the VCSEL. In addition, devices based on bulk active regions are known to the art. Thus, layer 14 may be viewed as a light generation layer which generates light due to spontaneous and stimulated emission via the recombination of electrons and holes generated by forward biasing the p-i-n diode.

The mirror regions are constructed from alternating layers of which layers 20 and 21 are typical. These layers have different indices of refraction. The thickness of each layer is chosen to be one quarter of the wavelength of the light that is to be output by the VCSEL. The stacked layers form Bragg mirrors. The stacks are typically constructed from alternating layers of AlAs or AlGaAs and GaAs or AlGaAs of lower Al concentration. The layers in the upper mirror region 18 are typically doped to be p-type semiconductors and those in the lower mirror region 19 are doped to be n-type semiconductors. Substrate 12 is preferably n-type contact. Bottom electrode 27 is preferably an n-ohmic contact. However, n-i-p diode

structures may also be constructed by growing the structures on a p-substrate or a semi-insulating substrate with a p-layer deposited thereon.

In one of the prior art designs discussed above, the current flow between electrodes 22 and 27 is confined to region 24 by implanting regions 25 and 26 to convert the regions to regions of high resistivity. This is typically accomplished by implanting with hydrogen ions. To provide sufficient current through the light generating region, electrode 22 must extend over the light generating region to some degree. As noted above, this overlap can cause a significant reduction in device efficiency in small VCSELs.

Refer now to Figure 2, which is a cross-sectional view of a VCSEL 300 according to one preferred embodiment of the present invention. VCSEL 100 utilizes a buried guide structure 301, which enables VCSEL 100 to have a smoother curve. To simplify the following discussion, those elements of VCSEL 100 that perform the same function as corresponding elements in Figure 1 have been given the same numeric designations.

In the preferred embodiment of the present invention, the guide structure is formed by ion-implantation or diffusion of species into one or more of the layers that make up the top mirror. Refer now to Figures 3(A)-3(E), which are cross-sectional views of a VCSEL according to the present invention at various stages in the fabrication process. The various layers need to provide the bottom mirror 210, active region 211, the first few layers of the top mirror 212 and a thin GaAs cap layer 234 are first fabricated in the conventional manner as shown in Figure 3(A). The GaAs cap layer is in the order of 50-100 Å thick and is positioned at one of the nulls of the optical field in the optical cavity. This arrangement minimizes the absorption of the light by this GaAs layer while protecting the underlying layers of the structure from oxidation.

The wafer on which the layers have been deposited is then removed from the epitaxial growth chamber. A mask 213 is then generated over the region that is to become the aperture of the guide structure. The mask is preferably generated by conventional lithographic techniques. The wafer is then implanted or diffused with atomic species to provide the

current-confinement regions 214 as shown in Figure 3(B). The particular species utilized will be discussed in more detail below.

After the introduction of the doping species, the mask is removed and the remaining layers 215 of the top mirror are deposited as shown in Figure 3(C). The implanted or diffused area must be preserved during the high temperature exposure of the altered region that is encountered during the growth of the remaining mirror layers.

After the deposition of the remaining layers 215 of the top mirror, a high resistive region 217 as shown in Figure 3(D) is created by an aggregated implantation to reduce the parasitic capacitance of the VCSEL under its top metal contact and bonding pad and to provide the necessary current confinement. If the individual VCSELs are part of an array in which the members are not isolated by cutting a trench between the members of the array, this aggregated implantation should be extended to beyond the light emitting layer to provide isolation of the individual VCSELs as shown at 227 in Figure 3(E). The isolation implant is constructed by masking the surface of the top mirror and then implanting the unmasked region with hydrogen ions to render the region non-conducting, or at least highly resistive. Since the isolation implant does not define the current confinement region in the device, the isolation implant does not need to extend over the aperture in the current-channeling structure. Hence, the problems discussed above with respect to such implants are not encountered in the present invention.

Finally, the top contact, which includes electrode 218, is deposited. This contact may include a grading layer and contact layers of the same conductivity type as the upper mirrors in addition to the metallic electrode.

The specific implants or diffusion species will now be discussed in more detail. To simplify the following discussion, the term "implant" shall be deemed to include the introduction of a species either by bombardment at an appropriate energy or by diffusion of the species into the material. Since the implanted region does not provide the current channeling function, it does not have to prevent current from flowing through the implant

region. For example, if the implanted region is to provide current confinement, it must have a resistivity greater than 5×10^6 ohm-cm.

The present invention is based on the observation that the aperture region also stabilizes the spatial modes of the VCSEL if the aperture structure is sufficiently close to the active region and certain heavy ions are used as the implantation elements. This mode stabilization results from altering the reflectivity of the mirror layers in the implanted region is altered. If this alteration takes place in a region in which the electric field of the active region is sufficiently strong, a smoothing of the output curve is observed. To achieve this effect, the aperture structure should be within 10 mirror pairs of the active region. The preferred ion species are Cr, Ti, and Fe; however, other heavy ions may also be utilized to alter the reflectivity of the mirror layers outside of the aperture.

The embodiments of the present invention described above have referred to top and bottom mirrors, etc. However, it will be obvious to those skilled in the art from the preceding discussion that these terms are convenient labels and do not imply any particular spatial orientation.

Various modifications to the present invention will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Accordingly, the present invention is to be limited solely by the scope of the following claims.

WHAT IS CLAIMED IS:

1. A laser diode comprising:

a bottom mirror comprising an electrically conducting material;

a first conductive spacer situated above said bottom mirror;

a light emitting layer;

a second conductive spacer situated above said light emitting material;

a top mirror comprising a plurality of mirror layers of a semiconducting material of a first conductivity type above said second conductive spacer in which adjacent layers have different indexes of refraction, and

an aperture defining layer comprising an aperture region and an implant region, said aperture region comprising an aperture semiconducting material of said first conductivity type, said implant region surrounding said aperture region and comprising an implant material that alters the reflectivity of said mirror layers in said implant region.

2. The laser diode of Claim 1 wherein said implant region is electrically conducting.

3. The laser diode of Claim 2 wherein said aperture defining layer is located within a distance equal to 20 mirror layers of said light emitting layer.

4. The laser diode of Claim 1 wherein said implant material comprises an element chosen from the group consisting of Cr, Ti, and Fe.

5. A method for fabricating a light-emitting device, said method comprising the steps of:

depositing a first semiconducting layer of a first conductivity type;

depositing a light-emitting layer on said first semiconducting layer;

depositing a second semiconducting layer of a second conductivity type on said light-emitting layer;

depositing an aperture defining layer on said second semiconducting layer, said aperture defining layer comprising a semiconducting material of said second conductivity type;

defining an aperture region in said aperture defining layer;

implanting an area around said aperture region with impurities to create a region having a reflectivity that is different from that in said aperture region, said aperture region remaining free of said impurities; and

depositing a third semiconducting layer of said second conductivity type on said second semiconducting layer after said implanting step.

6. The method of Claim 5 wherein said impurities comprise an element chosen from the group consisting of Cr, Ti, and Fe.

7. The method of Claim 5 wherein said first semiconducting layer comprises a plurality of sub-layers forming a DBR mirror.

8. The method of Claim 5 wherein said aperture defining layer comprises a plurality of sub-layers forming a portion of a DRB mirror, said third layer semiconducting layer comprising another portion of said DBR mirror.

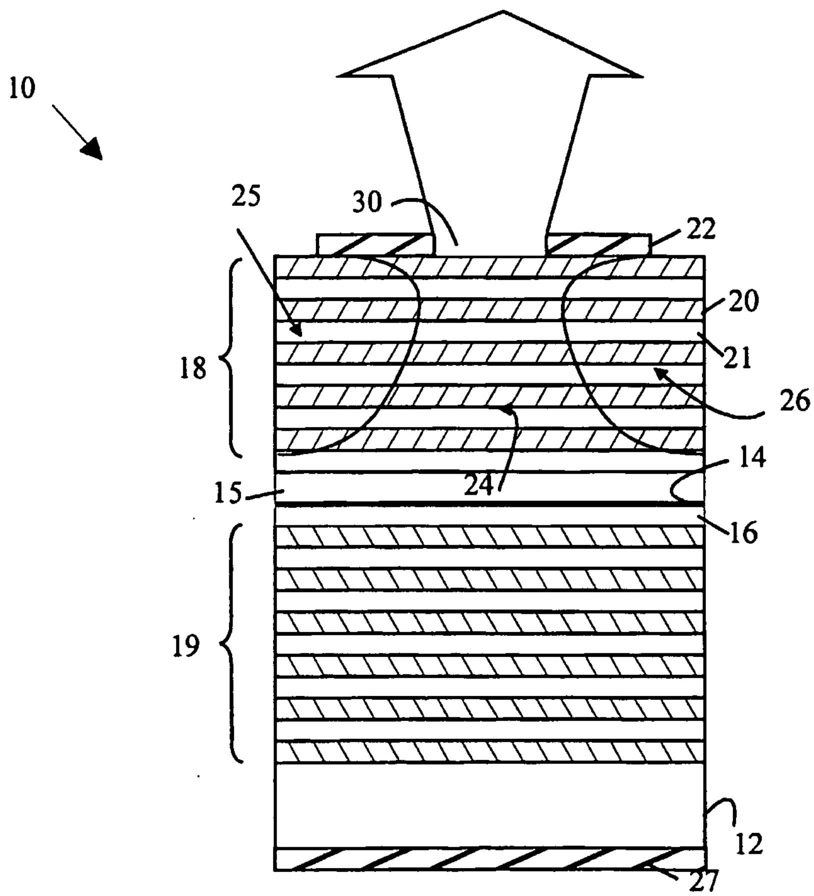


FIGURE 1
(PRIOR ART)

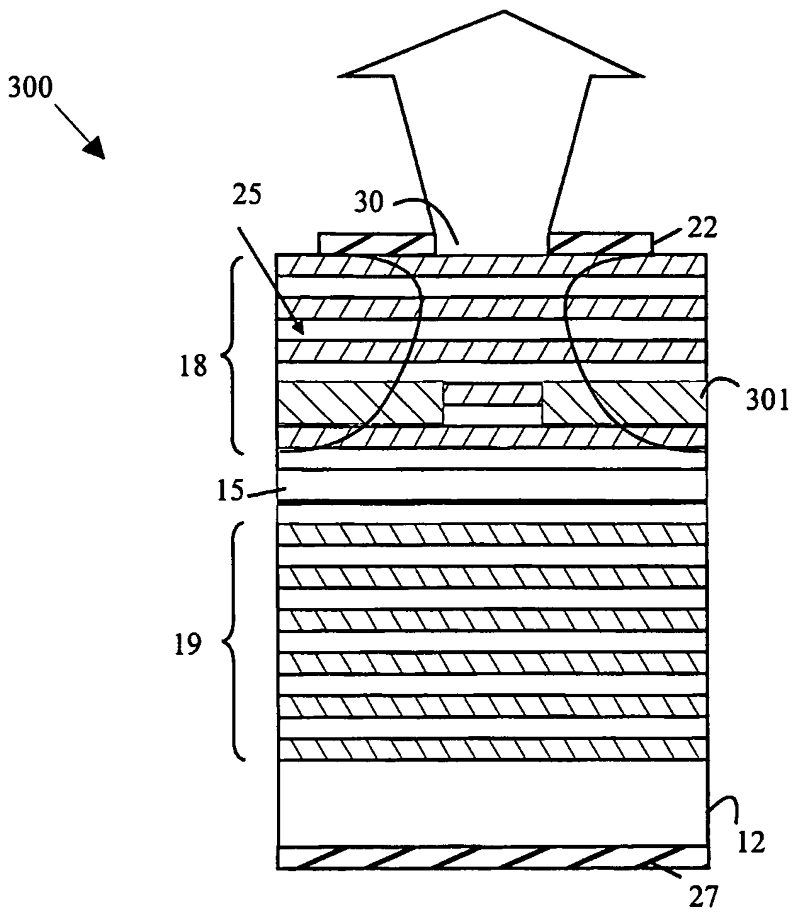


FIGURE 2

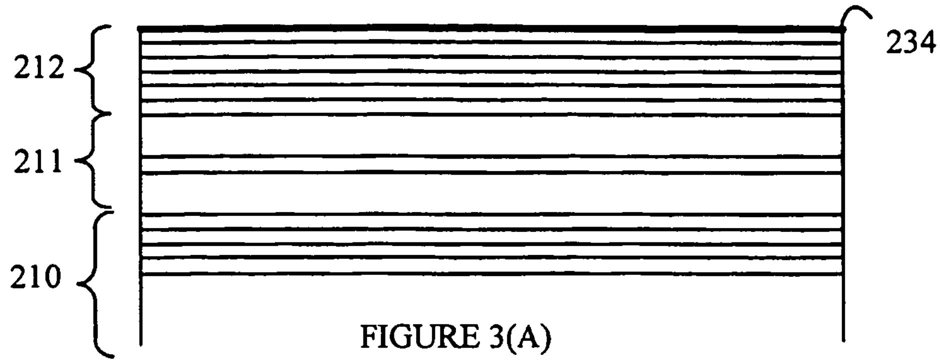


FIGURE 3(A)

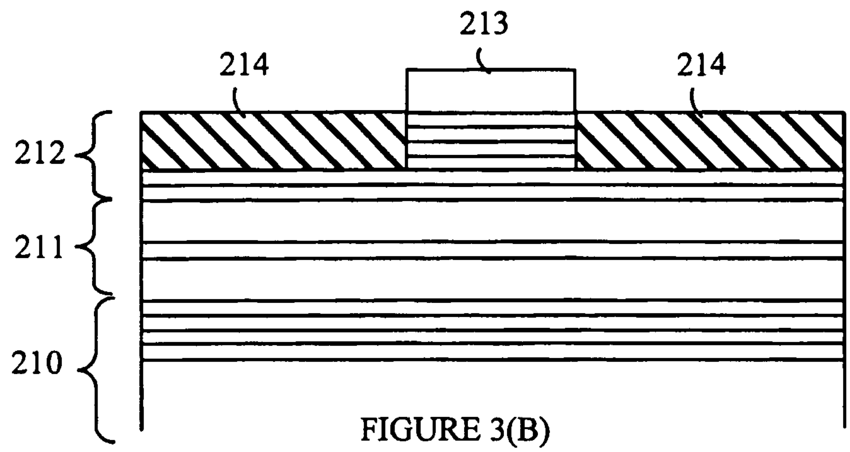


FIGURE 3(B)

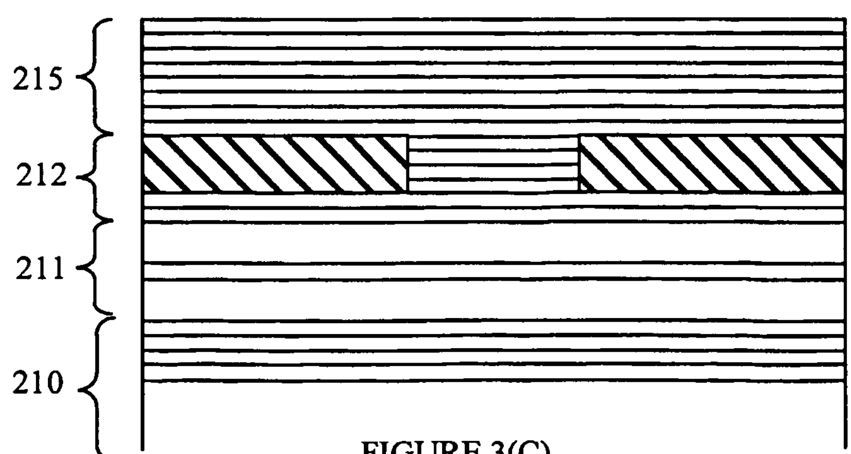


FIGURE 3(C)

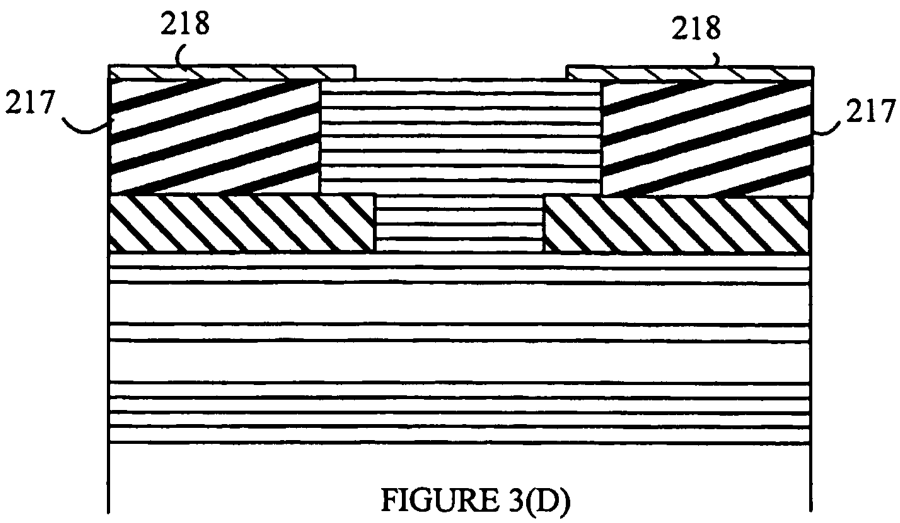


FIGURE 3(D)

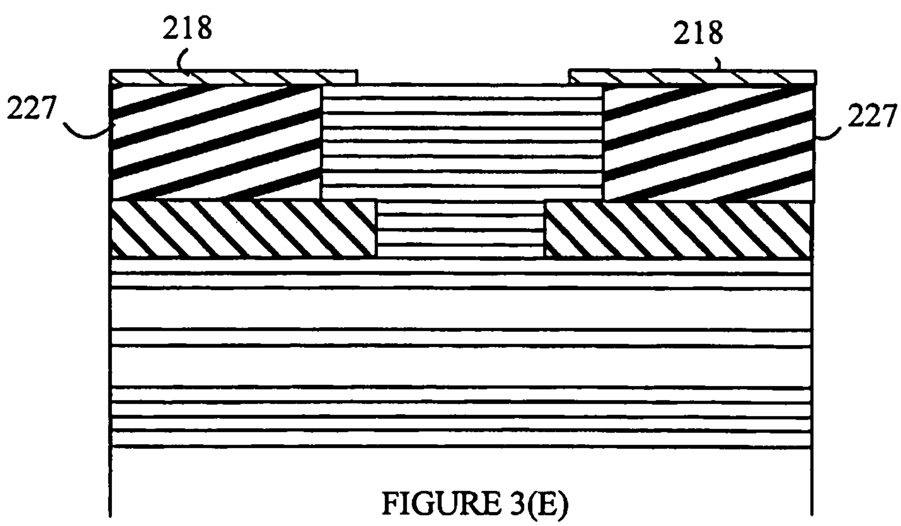


FIGURE 3(E)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/22770

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :H01S 3/08
US CL :372/43, 44, 45, 46, 49, 50, 96; 257/43, 370; 359/11, 22
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/43, 44, 45, 46, 49, 50, 96; 257/43, 370; 359/11, 22

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
USPTO APS EAST
search terms: laser diode, bottom mirror, first conductive spacer, second conductive spacer, top mirror, aperature layer

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,719,891 A (JEWELL) 17 February 1998 (17.02.1998), figures 4 and 5A-5F.	1-3,5,7,8
Y	US 6,128,109 A (JENKINS et al) 03 October 2000 (03.10.2000), column 29, lines 30-44.	4, 6
Y	US 5,903,589 A (JEWELL) 11 May 1999 (11.05.1999), figures 4 and 5A-5F.	1-8
Y	US 6,075,804 A (DEPPE et al) 13 June 2000 (13.06.2000), figure 7; abstract.	1-8
A	US 5,677,924 A (BESTWICK) 14 October 1997 (14.10.1997), figures 1-6.	1-8

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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